

Observation of s -channel production of single top quarks at the Tevatron

T. Aaltonen[†],²¹ V.M. Abazov[‡],¹³ B. Abbott[‡],¹¹⁶ B.S. Acharya[‡],⁸⁰ M. Adams[‡],⁹⁸ T. Adams[‡],⁹⁷ J.P. Agnew[‡],⁹⁴ G.D. Alexeev[‡],¹³ G. Alkhazov[‡],⁸⁸ A. Alton^{‡ii},³¹ S. Amerio^{†vv},³⁹ D. Amidei[†],³¹ A. Anastassov^{†v},¹⁵ A. Annovi[†],¹⁷ J. Antos[†],¹² G. Apollinari[†],¹⁵ J.A. Appel[†],¹⁵ T. Arisawa[†],⁵² A. Artikov[†],¹³ J. Asaadi[†],⁴⁷ W. Ashmanskas[†],¹⁵ A. Askew[‡],⁹⁷ S. Atkins[‡],¹⁰⁶ B. Auerbach[†],² K. Augsten[‡],⁶² A. Aurisano[†],⁴⁷ C. Avila[‡],⁶⁰ F. Azfar[†],³⁸ F. Badaud[‡],⁶⁵ W. Badgett[†],¹⁵ T. Bae[†],²⁵ L. Bagby[‡],¹⁵ B. Baldin[‡],¹⁵ D.V. Bandurin[‡],⁵¹ S. Banerjee[‡],⁸⁰ A. Barbaro-Galtieri[†],²⁶ E. Barberis[‡],¹⁰⁷ P. Baringer[‡],¹⁰⁵ V.E. Barnes[†],⁴³ B.A. Barnett[†],²³ P. Barria^{†xx},⁴¹ J.F. Bartlett[‡],¹⁵ P. Bartos[†],¹² U. Bässler[‡],⁷⁰ M. Bauce^{†vv},³⁹ V. Bazterra[‡],⁹⁸ A. Bean[†],¹⁰⁵ F. Bedeschi[†],⁴¹ M. Begalli[‡],⁵⁷ S. Behari[†],¹⁵ L. Bellantoni[‡],¹⁵ G. Bellettini^{†ww},⁴¹ J. Bellinger[†],⁵⁴ D. Benjamin[†],¹⁴ A. Beretvas[†],¹⁵ S.B. Beri[‡],⁷⁸ G. Bernardi[‡],⁶⁹ R. Bernhard[‡],⁷⁴ I. Bertram[‡],⁹² M. Besançon[‡],⁷⁰ R. Beuselinck[‡],⁹³ P.C. Bhat[‡],¹⁵ S. Bhatia[‡],¹⁰⁸ V. Bhatnagar[‡],⁷⁸ A. Bhatti[†],⁴⁵ K.R. Bland[†],⁵ G. Blazey[‡],⁹⁹ S. Blessing[‡],⁹⁷ K. Bloom[‡],¹⁰⁹ B. Blumenfeld[†],²³ A. Bocci[†],¹⁴ A. Bodek[†],⁴⁴ A. Boehnlein[‡],¹⁵ D. Boline[‡],¹¹³ E.E. Boos[‡],⁸⁶ G. Borissov[‡],⁹² D. Bortoletto[†],⁴³ M. Borysova^{†tt},⁹¹ J. Boudreau[†],⁴² A. Boveia[†],¹¹ A. Brandt[‡],¹¹⁹ O. Brandt[‡],⁷⁵ L. Brigliadori^{†uu},⁶ R. Brock[‡],³² C. Bromberg[†],³² A. Bross[‡],¹⁵ D. Brown[†],⁶⁹ E. Brucken[†],²¹ X.B. Bu[‡],¹⁵ J. Budagov[†],¹³ H.S. Budd[†],⁴⁴ M. Buehler[‡],¹⁵ V. Buescher[‡],⁷⁶ V. Bunichev[‡],⁸⁶ S. Burdin^{†jj},⁹² K. Burkett[†],¹⁵ G. Busetto^{†vv},³⁹ P. Bussey[†],¹⁹ C.P. Buszello[‡],⁹⁰ P. Butti^{†ww},⁴¹ A. Buzatu[†],¹⁹ A. Calamba[†],¹⁰ E. Camacho-Pérez[‡],⁸³ S. Camarda[†],⁴ M. Campanelli[†],²⁸ F. Canelli^{†cc},¹¹ B. Carls[†],²² D. Carlsmith[†],⁵⁴ R. Carosi[†],⁴¹ S. Carrillo^{†l},¹⁶ B. Casal^{†j},⁹ M. Casarsa[†],⁴⁸ B.C.K. Casey[‡],¹⁵ H. Castilla-Valdez[‡],⁸³ A. Castro^{†uu},⁶ P. Catastini[†],²⁰ S. Caughron[‡],³² D. Cauz^{†ccddd},⁴⁸ V. Cavaliere[†],²² M. Cavalli-Sforza[†],⁴ A. Cerri^{†e},²⁶ L. Cerrito^{†q},²⁸ S. Chakrabarti[‡],¹¹³ K.M. Chan[‡],¹⁰³ A. Chandra[‡],¹²¹ E. Chapon[‡],⁷⁰ G. Chen[‡],¹⁰⁵ Y.C. Chen[†],¹ M. Chertok[†],⁷ G. Chiarelli[†],⁴¹ G. Chlachidze[†],¹⁵ K. Cho[†],²⁵ S.W. Cho[†],⁸² S. Choi[‡],⁸² D. Chokheli[†],¹³ B. Choudhary[‡],⁷⁹ S. Cihangir[‡],¹⁵ D. Claes[‡],¹⁰⁹ A. Clark[†],¹⁸ C. Clarke[†],⁵³ J. Clutter[‡],¹⁰⁵ M.E. Convery[†],¹⁵ J. Conway[†],⁷ M. Cooke^{†ss},¹⁵ W.E. Cooper[‡],¹⁵ M. Corbo^{†y},¹⁵ M. Corcoran[†],¹²¹ M. Cordelli[†],¹⁷ F. Couderc[‡],⁷⁰ M.-C. Cousinou[‡],⁶⁷ C.A. Cox[†],⁷ D.J. Cox[†],⁷ M. Cremonesi[†],⁴¹ D. Cruz[†],⁴⁷ J. Cuevas^{†x},⁹ R. Culbertson[†],¹⁵ D. Cutts[‡],¹¹⁸ A. Das[‡],⁹⁵ N. d'Ascenzo^{†u},¹⁵ M. Datta^{†ff},¹⁵ G. Davies[‡],⁹³ P. de Barbaro[†],⁴⁴ S.J. de Jong[‡],^{84,85} E. De La Cruz-Burelo[‡],⁸³ F. Déliot[‡],⁷⁰ R. Demina[‡],⁴⁴ L. Demortier[†],⁴⁵ M. Deninno[†],⁶ D. Denisov[‡],¹⁵ S.P. Denisov[‡],⁸⁷ M. D'Errico^{†vv},³⁹ S. Desai[‡],¹⁵ C. Deterre^{†kk},⁷⁵ K. DeVaughan[‡],¹⁰⁹ F. Devoto[†],²¹ A. Di Canto^{†ww},⁴¹ B. Di Ruzza^{†p},¹⁵ H.T. Diehl[†],¹⁵ M. Diesburg[†],¹⁵ P.F. Ding[‡],⁹⁴ J.R. Dittmann[†],⁵ A. Dominguez[‡],¹⁰⁹ S. Donati^{†ww},⁴¹ M. D'Onofrio[†],²⁷ M. Dorigo^{†eee},⁴⁸ A. Driutti^{†ccddd},⁴⁸ A. Dubey[‡],⁷⁹ L.V. Dudko[‡],⁸⁶ A. Duperrin[‡],⁶⁷ S. Dutt[‡],⁷⁸ M. Eads[‡],⁹⁹ K. Ebina[†],⁵² R. Edgar[†],³¹ D. Edmunds[‡],³² A. Elagin[†],⁴⁷ J. Ellison[‡],⁹⁶ V.D. Elvira[‡],¹⁵ Y. Enari[‡],⁶⁹ R. Erbacher[†],⁷ S. Errede[†],²² B. Esham[†],²² H. Evans[‡],¹⁰¹ V.N. Evdokimov[‡],⁸⁷ S. Farrington[†],³⁸ L. Feng[‡],⁹⁹ T. Ferbel[‡],⁴⁴ J.P. Fernández Ramos[†],²⁹ F. Fiedler[‡],⁷⁶ R. Field[†],¹⁶ F. Filthaut[‡],^{84,85} W. Fisher[‡],³² H.E. Fisk[‡],¹⁵ G. Flanagan^{†s},¹⁵ R. Forrest[†],⁷ M. Fortner[‡],⁹⁹ H. Fox[‡],⁹² M. Franklin[†],²⁰ J.C. Freeman[†],¹⁵ H. Frisch[†],¹¹ S. Fuess[‡],¹⁵ Y. Funakoshi[†],⁵² C. Galloni^{†ww},⁴¹ P.H. Garbincius[‡],¹⁵ A. Garcia-Bellido[‡],⁴⁴ J.A. García-González[‡],⁸³ A.F. Garfinkel[†],⁴³ P. Garosi^{†xx},⁴¹ V. Gavrilov[‡],³³ W. Geng[‡],^{67,32} C.E. Gerber[‡],⁹⁸ H. Gerberich[†],²² E. Gerchtein[†],¹⁵ Y. Gershtein[‡],¹¹⁰ S. Giagu[†],⁴⁶ V. Giakoumopoulou[†],³ K. Gibson[†],⁴² C.M. Ginsburg[†],¹⁵ G. Ginter[‡],^{15,44} N. Giokaris[†],³ P. Giromini[†],¹⁷ G. Giurgiu[†],²³ V. Glagolev[†],¹³ D. Glenzinski[†],¹⁵ M. Gold[†],³⁴ D. Goldin[†],⁴⁷ A. Golossanov[†],¹⁵ G. Golovanov[‡],¹³ G. Gomez[†],⁹ G. Gomez-Ceballos[†],³⁰ M. Goncharov[†],³⁰ O. González López[†],²⁹ I. Gorelov[†],³⁴ A.T. Goshaw[†],¹⁴ K. Goulianos[†],⁴⁵ E. Gramellini[†],⁶ P.D. Grannis[‡],¹¹³ S. Greder[‡],⁷¹ H. Greenlee[‡],¹⁵ G. Grenier[‡],⁷² S. Grinstein[†],⁴ Ph. Gris[‡],⁶⁵ J.-F. Grivaz[‡],⁶⁸ A. Grohsjean^{†kk},⁷⁰ C. Grosso-Pilcher[†],¹¹ R.C. Group[†],^{51,15} S. Grünendahl[‡],¹⁵ M.W. Grünewald[‡],⁸¹ T. Guillemin[‡],⁶⁸ J. Guimaraes da Costa[†],²⁰ G. Gutierrez[‡],¹⁵ P. Gutierrez[‡],¹¹⁶ S.R. Hahn[†],¹⁵ J. Haley[‡],¹¹⁷ J.Y. Han[†],⁴⁴ L. Han[†],⁵⁹ F. Happacher[†],¹⁷ K. Hara[†],⁴⁹ K. Harder[‡],⁹⁴ M. Hare[†],⁵⁰ A. Harel[‡],⁴⁴ R.F. Harr[†],⁵³ T. Harrington-Taber^{†m},¹⁵ K. Hatakeyama[†],⁵ J.M. Hauptman[‡],¹⁰⁴ C. Hays[†],³⁸ J. Hays[‡],⁹³ T. Head[†],⁹⁴ T. Hebbeker[‡],⁷³ D. Hedin[‡],⁹⁹ H. Hegab[‡],¹¹⁷ J. Heinrich[†],⁴⁰ A.P. Heinson[‡],⁹⁶ U. Heintz[‡],¹¹⁸ C. Hensel[‡],⁵⁶ I. Heredia-De La Cruz^{†ll},⁸³ M. Herndon[†],⁵⁴ K. Herner[‡],¹⁵ G. Hesketh^{†nn},⁹⁴ M.D. Hildreth[‡],¹⁰³ R. Hirosky[‡],⁵¹ T. Hoang[‡],⁹⁷ J.D. Hobbs[‡],¹¹³ A. Hocker[†],¹⁵ B. Hoeneisen[‡],⁶⁴ J. Hogan[‡],¹²¹ M. Hohlfeld[‡],⁷⁶ J.L. Holzbauer[‡],¹⁰⁸ Z. Hong[†],⁴⁷ W. Hopkins^{†f},¹⁵ S. Hou[†],¹ I. Howley[‡],¹¹⁹

Z. Hubacek[‡],^{62,70} R.E. Hughes[†],³⁵ U. Husemann[†],⁵⁵ M. Hussein^{†aa},³² J. Huston[†],³² V. Hynek[‡],⁶² I. Iashvili[†],¹¹²
Y. Ilchenko[‡],¹²⁰ R. Illingworth[‡],¹⁵ G. Introzzi^{†zzaaa},⁴¹ M. Iori^{†bbb},⁴⁶ A.S. Ito[‡],¹⁵ A. Ivanov^{†o},⁷ S. Jabeen[‡],¹¹⁸
M. Jaffré[‡],⁶⁸ E. James[†],¹⁵ D. Jang[†],¹⁰ A. Jayasinghe[‡],¹¹⁶ B. Jayatilaka[†],¹⁵ E.J. Jeon[†],²⁵ M.S. Jeong[‡],⁸² R. Jesik[‡],⁹³
P. Jiang[‡],⁵⁹ S. Jindariani[†],¹⁵ K. Johns[‡],⁹⁵ E. Johnson[‡],³² M. Johnson[‡],¹⁵ A. Jonckheere[‡],¹⁵ M. Jones[†],⁴³
P. Jonsson[‡],⁹³ K.K. Joo[†],²⁵ J. Joshi[‡],⁹⁶ S.Y. Jun[†],¹⁰ A.W. Jung[‡],¹⁵ T.R. Junk[†],¹⁵ A. Juste[†],⁸⁹ E. Kajfasz[‡],⁶⁷
M. Kambeitz[†],²⁴ T. Kamon[†],^{25,47} P.E. Karchin[†],⁵³ D. Karmanov[‡],⁸⁶ A. Kasmi[†],⁵ Y. Kato^{†n},³⁷ I. Katsanos[‡],¹⁰⁹
R. Kehoe[‡],¹²⁰ S. Kermiche[‡],⁶⁷ W. Ketchum^{†gg},¹¹ J. Keung[†],⁴⁰ N. Khalatyan[‡],¹⁵ A. Khanov[†],¹¹⁷ A. Kharchilava[‡],¹¹²
Y.N. Kharzheev[†],¹³ B. Kilminster^{†cc},¹⁵ D.H. Kim[†],²⁵ H.S. Kim[†],²⁵ J.E. Kim[†],²⁵ M.J. Kim[†],¹⁷ S.H. Kim[†],⁴⁹
S.B. Kim[†],²⁵ Y.J. Kim[†],²⁵ Y.K. Kim[†],¹¹ N. Kimura[†],⁵² M. Kirby[†],¹⁵ I. Kiselevich[‡],³³ K. Knoepfel[†],¹⁵ J.M. Kohli[‡],⁷⁸
K. Kondo[†],⁵², * D.J. Kong[†],²⁵ J. Konigsberg[†],¹⁶ A.V. Kotwal[†],¹⁴ A.V. Kozelov[‡],⁸⁷ J. Kraus[‡],¹⁰⁸ M. Kreps[†],²⁴
J. Kroll[†],⁴⁰ M. Kruse[†],¹⁴ T. Kuhr[†],²⁴ A. Kumar[†],¹¹² A. Kupco[†],⁶³ M. Kurata[†],⁴⁹ T. Kurča[‡],⁷² V.A. Kuzmin[‡],⁸⁶
A.T. Laasanen[†],⁴³ S. Lammel[†],¹⁵ S. Lammers[‡],¹⁰¹ M. Lancaster[†],²⁸ K. Lannon^{†w},³⁵ G. Latino^{†xx},⁴¹ P. Lebrun[‡],⁷²
H.S. Lee[‡],⁸² H.S. Lee[†],²⁵ J.S. Lee[†],²⁵ S.W. Lee[‡],¹⁰⁴ W.M. Lee[‡],¹⁵ X. Lei[‡],⁹⁵ J. Lellouch[‡],⁶⁹ S. Leo[†],⁴¹ S. Leone[†],⁴¹
J.D. Lewis[†],¹⁵ D. Li[‡],⁶⁹ H. Li[‡],⁵¹ L. Li[‡],⁹⁶ Q.Z. Li[‡],¹⁵ J.K. Lim[‡],⁸² A. Limosani^{†r},¹⁴ D. Lincoln[‡],¹⁵ J. Linnemann[‡],³²
V.V. Lipaev[‡],⁸⁷ E. Lipeles[†],⁴⁰ R. Lipton[†],¹⁵ A. Lister^{†a},¹⁸ H. Liu[†],⁵¹ H. Liu[†],¹²⁰ Q. Liu[†],⁴³ T. Liu[†],¹⁵ Y. Liu[‡],⁵⁹
A. Lobodenko[‡],⁸⁸ S. Lockwitz[†],⁵⁵ A. Loginov[†],⁵⁵ M. Lokajicek[‡],⁶³ R. Lopes de Sa[‡],¹¹³ D. Lucchesi^{†vv},³⁹
A. Lucà[†],¹⁷ J. Lueck[†],²⁴ P. Lujan[†],²⁶ P. Lukens[†],¹⁵ R. Luna-Garcia^{†oo},⁸³ G. Lungu[†],⁴⁵ A.L. Lyon[†],¹⁵ J. Lys[†],²⁶
R. Lysak^{†d},¹² A.K.A. Maciel[‡],⁵⁶ R. Madar[‡],⁷⁴ R. Madrak[†],¹⁵ P. Maestro^{†xx},⁴¹ R. Magaña-Villalba[‡],⁸³ S. Malik[†],⁴⁵
S. Malik[‡],¹⁰⁹ V.L. Malyshev[‡],¹³ G. Manca^{†b},²⁷ A. Manousakis-Katsikakis[†],³ J. Mansour[†],⁷⁵ L. Marchese^{†hh},⁶
F. Margaroli[†],⁴⁶ P. Marino^{†yy},⁴¹ J. Martínez-Ortega[‡],⁸³ M. Martínez[†],⁴ K. Matera[†],²² M.E. Mattson[†],⁵³
A. Mazzacane[†],¹⁵ P. Mazzanti[†],⁶ R. McCarthy[‡],¹¹³ C.L. McGivern[†],⁹⁴ R. McNulty^{†i},²⁷ A. Mehta[†],²⁷ P. Mehtala[†],²¹
M.M. Meijer[‡],^{84,85} A. Melnitchouk[‡],¹⁵ D. Menezes[‡],⁹⁹ P.G. Mercadante[‡],⁵⁸ M. Merkin[‡],⁸⁶ C. Mesropian[†],⁴⁵
A. Meyer[‡],⁷³ J. Meyer^{†qq},⁷⁵ T. Miao[†],¹⁵ F. Miconi[‡],⁷¹ D. Mietlicki[†],³¹ A. Mitra[†],¹ H. Miyake[†],⁴⁹ S. Moed[†],¹⁵
N. Moggi[†],⁶ N.K. Mondal[‡],⁸⁰ C.S. Moon^{†yy},¹⁵ R. Moore^{†dee},¹⁵ M.J. Morello^{†yy},⁴¹ A. Mukherjee[†],¹⁵ M. Mulhearn[‡],⁵¹
Th. Muller[†],²⁴ P. Murat[†],¹⁵ M. Mussini^{†uu},⁶ J. Nachtman^{†m},¹⁵ Y. Nagai[†],⁴⁹ J. Naganoma[†],⁵² E. Nagy[‡],⁶⁷
I. Nakano[†],³⁶ A. Napier[†],⁵⁰ M. Narain[‡],¹¹⁸ R. Nayyar[‡],⁹⁵ H.A. Neal[‡],³¹ J.P. Negret[‡],⁶⁰ J. Nett[†],⁴⁷ C. Neu[†],⁵¹
P. Neustroev[‡],⁸⁸ H.T. Nguyen[‡],⁵¹ T. Nigmanov[†],⁴² L. Nodulman[†],² S.Y. Noh[†],²⁵ O. Norniella[†],²² T. Nunnemann[‡],⁷⁷
L. Oakes[†],³⁸ S.H. Oh[†],¹⁴ Y.D. Oh[†],²⁵ I. Oksuzian[†],⁵¹ T. Okusawa[†],³⁷ R. Orava[†],²¹ J. Orduna[†],¹²¹ L. Ortolan[†],⁴
N. Osman[‡],⁶⁷ J. Osta[†],¹⁰³ C. Pagliarone[†],⁴⁸ A. Pal[‡],¹¹⁹ E. Palencia^{†e},⁹ P. Palmi[†],³⁴ V. Papadimitriou[†],¹⁵
N. Parashar[†],¹⁰² V. Parihar[†],¹¹⁸ S.K. Park[‡],⁸² W. Parker[†],⁵⁴ R. Partridge^{†mm},¹¹⁸ N. Parua[†],¹⁰¹ A. Patwa^{†rr},¹¹⁴
G. Pauletta^{†ccddd},⁴⁸ M. Paulini[†],¹⁰ C. Paus[†],³⁰ B. Penning[†],¹⁵ M. Perfilov[†],⁸⁶ Y. Peters[†],⁹⁴ K. Petridis[‡],⁹⁴
G. Petrillo[†],⁴⁴ P. Pétroff[†],⁶⁸ T.J. Phillips[†],¹⁴ G. Piacentino[†],⁴¹ E. Pianori[†],⁴⁰ J. Pilot[†],⁷ K. Pitts[†],²² C. Plager[†],⁸
M.-A. Pleier[‡],¹¹⁴ V.M. Podstavkov[†],¹⁵ L. Pondrom[†],⁵⁴ A.V. Popov[‡],⁸⁷ S. Poprocki^{†f},¹⁵ K. Potamianos[†],²⁶
A. Pranko[†],²⁶ M. Prewitt[‡],¹²¹ D. Price[‡],⁹⁴ N. Prokopenko[‡],⁸⁷ F. Prokoshin^{†z},¹³ F. Ptohos^{†g},¹⁷ G. Punzi^{†ww},⁴¹
J. Qian[‡],³¹ A. Quadt[‡],⁷⁵ B. Quinn[‡],¹⁰⁸ N. Ranjan[†],⁴³ P.N. Ratoff[†],⁹² I. Razumov[‡],⁸⁷ I. Redondo Fernández[†],²⁹
P. Renton[†],³⁸ M. Rescigno[†],⁴⁶ F. Rimondi[†],⁶, * I. Ripp-Baudot[†],⁷¹ L. Ristori[†],^{41,15} F. Rizatdinova[†],¹¹⁷
A. Robson[†],¹⁹ T. Rodriguez[†],⁴⁰ S. Rolli^{†h},⁵⁰ M. Rominsky[†],¹⁵ M. Ronzani^{†ww},⁴¹ R. Roser[†],¹⁵ J.L. Rosner[†],¹¹
A. Ross[‡],⁹² C. Royon[‡],⁷⁰ P. Rubinov[‡],¹⁵ R. Ruchti[‡],¹⁰³ F. Ruffini^{†xx},⁴¹ A. Ruiz[†],⁹ J. Russ[†],¹⁰ V. Rusu[†],¹⁵
G. Sajot[‡],⁶⁶ W.K. Sakumoto[†],⁴⁴ Y. Sakurai[†],⁵² A. Sánchez-Hernández[‡],⁸³ M.P. Sanders[†],⁷⁷ L. Santi^{†ccddd},⁴⁸
A.S. Santos^{†pp},⁵⁶ K. Sato[†],⁴⁹ G. Savage[‡],¹⁵ V. Saveliev^{†u},¹⁵ A. Savoy-Navarro^{†y},¹⁵ L. Sawyer[‡],¹⁰⁶ T. Scanlon[‡],⁹³
R.D. Schamberger[‡],¹¹³ Y. Scheglov[‡],⁸⁸ H. Schellman[‡],¹⁰⁰ P. Schlabach[†],¹⁵ E.E. Schmidt[†],¹⁵ C. Schwanenberger[‡],⁹⁴
T. Schwarz[†],³¹ R. Schwienhorst[‡],³² L. Scodellaro[†],⁹ F. Seuri[†],⁴¹ S. Seidel[†],³⁴ Y. Seiya[†],³⁷ J. Sekaric[‡],¹⁰⁵
A. Semenov[†],¹³ H. Severini[‡],¹¹⁶ F. Sforza^{†ww},⁴¹ E. Shabalina[‡],⁷⁵ S.Z. Shalhout[†],⁷ V. Shary[†],⁷⁰ S. Shaw[†],³²
A.A. Shchukin[‡],⁸⁷ T. Shears[†],²⁷ P.F. Shepard[†],⁴² M. Shimojima^{†t},⁴⁹ M. Shochet[†],¹¹ I. Shreyber-Tecker[†],³³
V. Simak[‡],⁶² A. Simonenko[†],¹³ P. Skubic[‡],¹¹⁶ P. Slattery[‡],⁴⁴ K. Sliwa[†],⁵⁰ D. Smirnov[‡],¹⁰³ J.R. Smith[†],⁷
F.D. Snider[†],¹⁵ G.R. Snow[‡],¹⁰⁹ J. Snow[‡],¹¹⁵ S. Snyder[‡],¹¹⁴ S. Söldner-Rembold[‡],⁹⁴ H. Song[†],⁴² L. Sonnenschein[‡],⁷³
V. Sorin[†],⁴ K. Soustruznik[‡],⁶¹ R. St. Denis[†],¹⁹, * M. Stancari[†],¹⁵ J. Stark[‡],⁶⁶ D. Stentz^{†v},¹⁵ D.A. Stoyanova[‡],⁸⁷
M. Strauss[‡],¹¹⁶ J. Strologas[†],³⁴ Y. Sudo[†],⁴⁹ A. Sukhanov[†],¹⁵ I. Suslov[†],¹³ L. Suter[†],⁹⁴ P. Svoisky[‡],¹¹⁶
K. Takemasa[†],⁴⁹ Y. Takeuchi[†],⁴⁹ J. Tang[†],¹¹ M. Tecchio[†],³¹ P.K. Teng[†],¹ J. Thom^{†f},¹⁵ E. Thomson[†],⁴⁰
V. Thukral[†],⁴⁷ M. Titov[‡],⁷⁰ D. Toback[†],⁴⁷ S. Tokar[†],¹² V.V. Tokmenin[‡],¹³ K. Tollefson[†],³² T. Tomura[†],⁴⁹
D. Tonelli^{†e},¹⁵ S. Torre[†],¹⁷ D. Torretta[†],¹⁵ P. Totaro[†],³⁹ M. Trovato^{†yy},⁴¹ Y.-T. Tsai[‡],⁴⁴ D. Tsybychev[‡],¹¹³

B. Tuchming[‡],⁷⁰ C. Tully[‡],¹¹¹ F. Ukegawa[‡],⁴⁹ S. Uozumi[†],²⁵ L. Uvarov[‡],⁸⁸ S. Uvarov[‡],⁸⁸ S. Uzunyan[‡],⁹⁹
 R. Van Kooten[‡],¹⁰¹ W.M. van Leeuwen[‡],⁸⁴ N. Varelas[‡],⁹⁸ E.W. Varnes[‡],⁹⁵ I.A. Vasilyev[‡],⁸⁷ F. Vázquez^{†l},¹⁶
 G. Velev[†],¹⁵ C. Vellidis[†],¹⁵ A.Y. Verkhnev[‡],¹³ C. Vernieri^{†yy},⁴¹ L.S. Vertogradov[‡],¹³ M. Verzocchi[‡],¹⁵
 M. Vesterinen[‡],⁹⁴ M. Vidal[†],⁴³ D. Vilanova[‡],⁷⁰ R. Vilar[†],⁹ J. Vizán^{†bb},⁹ M. Vogel[†],³⁴ P. Vokac[‡],⁶² G. Volpi[†],¹⁷
 P. Wagner[†],⁴⁰ H.D. Wahl[†],⁹⁷ R. Wallny^{†j},¹⁵ M.H.L.S. Wang[‡],¹⁵ S.M. Wang[†],¹ J. Warchol[‡],¹⁰³ D. Waters[†],²⁸
 G. Watts[‡],¹²² M. Wayne[‡],¹⁰³ J. Weichert[‡],⁷⁶ L. Welty-Rieger[‡],¹⁰⁰ W.C. Wester III[†],¹⁵ D. Whiteson^{†c},⁴⁰
 A.B. Wicklund[†],² S. Wilbur[†],⁷ H.H. Williams[†],⁴⁰ M.R.J. Williams[‡],¹⁰¹ G.W. Wilson[‡],¹⁰⁵ J.S. Wilson[†],³¹
 P. Wilson[†],¹⁵ B.L. Winer[†],³⁵ P. Wittich^{†f},¹⁵ M. Wobisch[‡],¹⁰⁶ S. Wolbers[†],¹⁵ H. Wolfe[†],³⁵ D.R. Wood[‡],¹⁰⁷
 T. Wright[†],³¹ X. Wu[†],¹⁸ Z. Wu[†],⁵ T.R. Wyatt[‡],⁹⁴ Y. Xie[‡],¹⁵ R. Yamada[‡],¹⁵ K. Yamamoto[†],³⁷ D. Yamato[†],³⁷
 S. Yang[‡],⁵⁹ T. Yang[†],¹⁵ U.K. Yang[†],²⁵ Y.C. Yang[†],²⁵ W.-M. Yao[†],²⁶ T. Yasuda[‡],¹⁵ Y.A. Yatsunenko[‡],¹³
 W. Ye[†],¹¹³ Z. Ye[†],¹⁵ G.P. Yeh[†],¹⁵ K. Yi^{†m},¹⁵ H. Yin[†],¹⁵ K. Yip[†],¹¹⁴ J. Yoh[†],¹⁵ K. Yorita[†],⁵² T. Yoshida^{†k},³⁷
 S.W. Youn[‡],¹⁵ G.B. Yu[†],¹⁴ I. Yu[†],²⁵ J.M. Yu[‡],³¹ A.M. Zanetti[†],⁴⁸ Y. Zeng[†],¹⁴ J. Zennaro[‡],¹¹² T.G. Zhao[†],⁹⁴
 B. Zhou[‡],³¹ C. Zhou[†],¹⁴ J. Zhu[‡],³¹ M. Zielinski[‡],⁴⁴ D. Zieminska[‡],¹⁰¹ L. Zivkovic[‡],⁶⁹ and S. Zucchelli^{†uu6}

(CDF Collaboration)[†]

(D0 Collaboration)[‡]

¹*Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China*

²*Argonne National Laboratory, Argonne, Illinois 60439, USA*

³*University of Athens, 157 71 Athens, Greece*

⁴*Institut de Física d'Altes Energies, ICREA, Universitat Autònoma de Barcelona, E-08193, Bellaterra (Barcelona), Spain*

⁵*Baylor University, Waco, Texas 76798, USA*

⁶*Istituto Nazionale di Fisica Nucleare Bologna, ^{uu}University of Bologna, I-40127 Bologna, Italy*

⁷*University of California, Davis, Davis, California 95616, USA*

⁸*University of California, Los Angeles, Los Angeles, California 90024, USA*

⁹*Instituto de Física de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*

¹⁰*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*

¹¹*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA*

¹²*Comenius University, 842 48 Bratislava, Slovakia; Institute of Experimental Physics, 040 01 Kosice, Slovakia*

¹³*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*

¹⁴*Duke University, Durham, North Carolina 27708, USA*

¹⁵*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*

¹⁶*University of Florida, Gainesville, Florida 32611, USA*

¹⁷*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*

¹⁸*University of Geneva, CH-1211 Geneva 4, Switzerland*

¹⁹*Glasgow University, Glasgow G12 8QQ, United Kingdom*

²⁰*Harvard University, Cambridge, Massachusetts 02138, USA*

²¹*Division of High Energy Physics, Department of Physics, University of Helsinki,*

FIN-00014, Helsinki, Finland; Helsinki Institute of Physics, FIN-00014, Helsinki, Finland

²²*University of Illinois, Urbana, Illinois 61801, USA*

²³*The Johns Hopkins University, Baltimore, Maryland 21218, USA*

²⁴*Institut für Experimentelle Kernphysik, Karlsruhe Institute of Technology, D-76131 Karlsruhe, Germany*

²⁵*Center for High Energy Physics: Kyungpook National University,*

Daegu 702-701, Korea; Seoul National University, Seoul 151-742,

Korea; Sungkyunkwan University, Suwon 440-746,

Korea; Korea Institute of Science and Technology Information,

Daejeon 305-806, Korea; Chonnam National University,

Gwangju 500-757, Korea; Chonbuk National University, Jeonju 561-756,

Korea; Ewha Womans University, Seoul, 120-750, Korea

²⁶*Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

²⁷*University of Liverpool, Liverpool L69 7ZE, United Kingdom*

²⁸*University College London, London WC1E 6BT, United Kingdom*

²⁹*Centro de Investigaciones Energeticas Medioambientales y Tecnológicas, E-28040 Madrid, Spain*

³⁰*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

³¹*University of Michigan, Ann Arbor, Michigan 48109, USA*

³²*Michigan State University, East Lansing, Michigan 48824, USA*

³³*Institution for Theoretical and Experimental Physics, ITEP, Moscow 117259, Russia*

³⁴*University of New Mexico, Albuquerque, New Mexico 87131, USA*

³⁵*The Ohio State University, Columbus, Ohio 43210, USA*

³⁶*Okayama University, Okayama 700-8530, Japan*

³⁷*Osaka City University, Osaka 558-8585, Japan*

³⁸*University of Oxford, Oxford OX1 3RH, United Kingdom*

- ³⁹*Istituto Nazionale di Fisica Nucleare, Sezione di Padova, ^{vv} University of Padova, I-35131 Padova, Italy*
- ⁴⁰*University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*
- ⁴¹*Istituto Nazionale di Fisica Nucleare Pisa, ^{ww} University of Pisa, ^{xx} University of Siena, ^{yy} Scuola Normale Superiore, I-56127 Pisa, Italy, ^{zz} INFN Pavia, I-27100 Pavia, Italy, ^{aaa} University of Pavia, I-27100 Pavia, Italy*
- ⁴²*University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA*
- ⁴³*Purdue University, West Lafayette, Indiana 47907, USA*
- ⁴⁴*University of Rochester, Rochester, New York 14627, USA*
- ⁴⁵*The Rockefeller University, New York, New York 10065, USA*
- ⁴⁶*Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1, ^{bbb} Sapienza Università di Roma, I-00185 Roma, Italy*
- ⁴⁷*Mitchell Institute for Fundamental Physics and Astronomy, Texas A&M University, College Station, Texas 77843, USA*
- ⁴⁸*Istituto Nazionale di Fisica Nucleare Trieste, ^{ccc} Gruppo Collegato di Udine, ^{ddd} University of Udine, I-33100 Udine, Italy, ^{eee} University of Trieste, I-34127 Trieste, Italy*
- ⁴⁹*University of Tsukuba, Tsukuba, Ibaraki 305, Japan*
- ⁵⁰*Tufts University, Medford, Massachusetts 02155, USA*
- ⁵¹*University of Virginia, Charlottesville, Virginia 22906, USA*
- ⁵²*Waseda University, Tokyo 169, Japan*
- ⁵³*Wayne State University, Detroit, Michigan 48201, USA*
- ⁵⁴*University of Wisconsin, Madison, Wisconsin 53706, USA*
- ⁵⁵*Yale University, New Haven, Connecticut 06520, USA*
- ⁵⁶*LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*
- ⁵⁷*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
- ⁵⁸*Universidade Federal do ABC, Santo André, Brazil*
- ⁵⁹*University of Science and Technology of China, Hefei, People's Republic of China*
- ⁶⁰*Universidad de los Andes, Bogotá, Colombia*
- ⁶¹*Charles University, Faculty of Mathematics and Physics, Center for Particle Physics, Prague, Czech Republic*
- ⁶²*Czech Technical University in Prague, Prague, Czech Republic*
- ⁶³*Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic*
- ⁶⁴*Universidad San Francisco de Quito, Quito, Ecuador*
- ⁶⁵*LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France*
- ⁶⁶*LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, Grenoble, France*
- ⁶⁷*CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France*
- ⁶⁸*LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France*
- ⁶⁹*LPNHE, Universités Paris VI and VII, CNRS/IN2P3, Paris, France*
- ⁷⁰*CEA, Irfu, SPP, Saclay, France*
- ⁷¹*IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France*
- ⁷²*IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France*
- ⁷³*III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany*
- ⁷⁴*Physikalisches Institut, Universität Freiburg, Freiburg, Germany*
- ⁷⁵*II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany*
- ⁷⁶*Institut für Physik, Universität Mainz, Mainz, Germany*
- ⁷⁷*Ludwig-Maximilians-Universität München, München, Germany*
- ⁷⁸*Panjab University, Chandigarh, India*
- ⁷⁹*Delhi University, Delhi, India*
- ⁸⁰*Tata Institute of Fundamental Research, Mumbai, India*
- ⁸¹*University College Dublin, Dublin, Ireland*
- ⁸²*Korea Detector Laboratory, Korea University, Seoul, Korea*
- ⁸³*CINVESTAV, Mexico City, Mexico*
- ⁸⁴*Nikhef, Science Park, Amsterdam, the Netherlands*
- ⁸⁵*Radboud University Nijmegen, Nijmegen, the Netherlands*
- ⁸⁶*Moscow State University, Moscow, Russia*
- ⁸⁷*Institute for High Energy Physics, Protvino, Russia*
- ⁸⁸*Petersburg Nuclear Physics Institute, St. Petersburg, Russia*
- ⁸⁹*Institució Catalana de Recerca i Estudis Avançats (ICREA) and Institut de Física d'Altes Energies (IFAE), Barcelona, Spain*
- ⁹⁰*Uppsala University, Uppsala, Sweden*
- ⁹¹*Taras Shevchenko National University of Kyiv, Kiev, Ukraine*
- ⁹²*Lancaster University, Lancaster LA1 4YB, United Kingdom*
- ⁹³*Imperial College London, London SW7 2AZ, United Kingdom*
- ⁹⁴*The University of Manchester, Manchester M13 9PL, United Kingdom*

- ⁹⁵University of Arizona, Tucson, Arizona 85721, USA
⁹⁶University of California Riverside, Riverside, California 92521, USA
⁹⁷Florida State University, Tallahassee, Florida 32306, USA
⁹⁸University of Illinois at Chicago, Chicago, Illinois 60607, USA
⁹⁹Northern Illinois University, DeKalb, Illinois 60115, USA
¹⁰⁰Northwestern University, Evanston, Illinois 60208, USA
¹⁰¹Indiana University, Bloomington, Indiana 47405, USA
¹⁰²Purdue University Calumet, Hammond, Indiana 46323, USA
¹⁰³University of Notre Dame, Notre Dame, Indiana 46556, USA
¹⁰⁴Iowa State University, Ames, Iowa 50011, USA
¹⁰⁵University of Kansas, Lawrence, Kansas 66045, USA
¹⁰⁶Louisiana Tech University, Ruston, Louisiana 71272, USA
¹⁰⁷Northeastern University, Boston, Massachusetts 02115, USA
¹⁰⁸University of Mississippi, University, Mississippi 38677, USA
¹⁰⁹University of Nebraska, Lincoln, Nebraska 68588, USA
¹¹⁰Rutgers University, Piscataway, New Jersey 08855, USA
¹¹¹Princeton University, Princeton, New Jersey 08544, USA
¹¹²State University of New York, Buffalo, New York 14260, USA
¹¹³State University of New York, Stony Brook, New York 11794, USA
¹¹⁴Brookhaven National Laboratory, Upton, New York 11973, USA
¹¹⁵Langston University, Langston, Oklahoma 73050, USA
¹¹⁶University of Oklahoma, Norman, Oklahoma 73019, USA
¹¹⁷Oklahoma State University, Stillwater, Oklahoma 74078, USA
¹¹⁸Brown University, Providence, Rhode Island 02912, USA
¹¹⁹University of Texas, Arlington, Texas 76019, USA
¹²⁰Southern Methodist University, Dallas, Texas 75275, USA
¹²¹Rice University, Houston, Texas 77005, USA
¹²²University of Washington, Seattle, Washington 98195, USA
- (Dated: February 18, 2014)

We report first observation of single-top-quark production in the s -channel through the combination of the CDF and D0 measurements of the cross section in proton-antiproton collisions at a center-of-mass energy of 1.96 TeV. The data correspond to total integrated luminosities of up to 9.7 fb^{-1} per experiment. The measured cross section is $\sigma_s = 1.29^{+0.26}_{-0.24} \text{ pb}$. The probability of observing a statistical fluctuation of the background to a cross section of the observed size or larger is 1.8×10^{-10} , corresponding to a significance of 6.3 standard deviations for the presence of s -channel contribution to the production of single-top quarks.

PACS numbers: 14.65.Ha; 12.15.Ji; 13.85.Qk; 12.15.Hh

1 The top quark, with a mass of $m_t = 173.2 \pm 21$
2 0.9 GeV [1], is the most massive and one of the most puz-
3 zling elementary particles of the standard model (SM).
4 Detailed studies of top-quark production and decay pro-
5 vide powerful tests of strong and electroweak interac-
6 tions, as well as sensitivity to physics beyond the stan-
7 dard model (BSM) [2], especially involving particles that
8 couple strongly to mass. At the Tevatron, where protons
9 (p) and antiprotons (\bar{p}) collide at a center-of-mass energy
10 of $\sqrt{s} = 1.96 \text{ TeV}$, top quarks are produced predomi-
11 nantly in pairs ($t\bar{t}$) via the strong interaction [3]. Top
12 quarks are also produced singly in $p\bar{p}$ collisions via the
13 electroweak interaction. The single-top-quark produc-
14 tion cross section is expected to be proportional to the
15 square of the magnitude of the quark-mixing Cabibbo-
16 Kobayashi-Maskawa matrix [4] element V_{tb} , and conse-
17 quently sensitive to potential contributions from a fourth
18 generation of quarks [5, 6], as well as flavor-changing neu-
19 tral currents [7–10], anomalous top-quark couplings [11–
20 13], heavy W' bosons [14–17] or supersymmetric charged

Higgs bosons [18, 19], and other new phenomena [20, 21].

At the Tevatron, there are two important processes in which a single top quark is produced in association with other quarks. The dominant channel proceeds through the exchange of a space-like virtual W boson between a light quark and a bottom quark in the t -channel [22–24]. A second mode occurs through the exchange of a time-like virtual W boson in the s -channel, which produces a top quark and a bottom quark [26]. Figure 1 shows the leading Feynman diagrams for the s -channel and t -channel production modes.

Independent measurements of s -channel and t -channel production are important, since BSM contributions could have different effects on the two modes [20].

Single-top-quark production, independent of channel, was reported by the CDF and D0 collaborations in Refs. [27] and [28, 29], respectively. The D0 collaboration subsequently measured with larger data sets the production cross section for the combined s and t -channels [30], and obtained $\sigma_{s+t} = 4.11^{+0.59}_{-0.55} \text{ pb}$ using a data set of

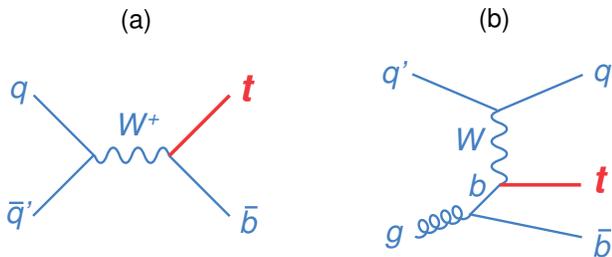


FIG. 1: Dominant Feynman diagrams for (a) s -channel and (b) t -channel single-top-quark production at the Tevatron.

9.7 fb⁻¹ [30] in agreement with the SM prediction of 3.15 ± 0.19 pb ($m_t = 172.5$ GeV) [24, 25].

After establishing the $s + t$ process, effort was redirected to independently measuring the cross sections of the individual production modes. Several differences in the properties of s and t -channel events can be used to help distinguish them from one another. Events originating from t -channel production typically contain one light-flavor jet in the forward detector region (at large pseudorapidity), which is useful for distinguishing them from events associated with s -channel production and other SM background processes. Moreover, events from the s -channel process are more likely to contain two jets originating from b quarks (b jets) within the central region of the detector where they can be identified. Hence, single-top-like events with two identified b jets are more likely to have originated from s -channel production. Exploiting these differences, the D0 collaboration observed the t -channel process separately [31], and measured its cross section to be $\sigma_t = 2.90 \pm 0.59$ pb. This compares to the SM prediction of 2.10 ± 0.13 pb ($m_t = 172.5$ GeV) [24].

At the CERN LHC proton-proton collider, t -channel production was also observed by the ATLAS and CMS collaborations [32, 33]. At the Tevatron the cross section for the s -channel process is expected to be smaller than that of the t -channel and its event kinematics are less distinct from the background. Recently, the CDF and D0 collaborations have reported evidence for s -channel production independently of each other [30, 34]. The s -channel measurement is even more difficult at the LHC, as proton-proton collisions yield a smaller signal-to-background ratio compared to the Tevatron. Therefore, the Tevatron offers a promising opportunity to study s -channel single-top-quark production. To date, the LHC experiments have provided upper limits on the s -channel production cross section.

In this Letter we report a combination of s -channel cross section measurements performed by the CDF [34, 35] and D0 [30] collaborations. The CDF and D0 detectors are central magnetic spectrometers surrounded by electromagnetic and hadronic calorimeters and muon de-

82 tectors [36–38]. The combined measurement utilizes the
83 full Tevatron Run II data sets corresponding to up to
84 9.7 fb⁻¹ of integrated luminosity per experiment.

85 Since the magnitude of the W -top-bottom quark
86 coupling is much larger than the W -top-down and W -top-
87 strange quark couplings, each top quark decays almost
88 exclusively to a W boson and a b quark. The event selection
89 is split into two distinct final-state topologies, both
90 designed to select single-top-quark events in which the
91 W boson decays leptonically.

92 One final-state topology (ℓ +jets), analyzed by both
93 collaborations, contains single-top-quark events in which
94 the W boson decays leptonically ($W \rightarrow \ell\nu_\ell$), selecting
95 events that (i) contain only one isolated lepton ($\ell = e$
96 or μ) with large transverse momentum (p_T), (ii) have
97 large \cancel{E}_T , (iii) have either two jets (CDF analysis) or two
98 or three jets (D0 analysis) with large p_T , and (iv) have
99 one or two b jets. To identify b jets, multivariate techniques
100 are used that discriminate b jets from jets originating
101 from light quarks and gluons [39, 40]. Additional
102 selection criteria are applied to exclude kinematic regions
103 that are difficult to model, and to minimize the quantum
104 chromodynamics (QCD) multijet background where one
105 jet is misreconstructed as a lepton and spurious \cancel{E}_T arises
106 from jet energy mismeasurements.

107 The other final-state topology, analyzed by the CDF
108 collaboration, involves \cancel{E}_T and jets, but no reconstructed
109 isolated charged leptons (\cancel{E}_T +jets) [38]. The CDF analysis
110 avoids overlap with the ℓ +jets sample by explicitly
111 vetoing events with identified leptons [35]. Large missing
112 transverse energy is required and events with two or three
113 reconstructed jets are accepted. This additional sample
114 increases the acceptance for s -channel signal events by
115 encompassing those in which the W -boson decay produces
116 a muon or electron that is either not reconstructed or
117 not isolated; or is a hadronically decaying tau lepton
118 that is reconstructed as a third jet. After the basic event
119 selection, QCD multijet events dominate the \cancel{E}_T +jets
120 event sample. To reduce this multijet background, a neural-
121 network event selection is optimized to preferentially
122 select signal-like events.

123 Events passing the ℓ +jets and \cancel{E}_T +jets selections are
124 further separated into independent analysis channels
125 based on the number of reconstructed jets as well as
126 the number and quality of b -tagged jets. Each of the
127 analyzed channels has a different background composition
128 and signal (s) to background (b) ratio and analyzing
129 them separately enhances the sensitivity to single-top-
130 quark production [30, 34, 35].

131 Both collaborations use Monte Carlo (MC) generators
132 to simulate the kinematic properties of signal and back-
133 ground events, except in the case of multijet production,
134 for which the model is derived from data. The CDF
135 analysis models single-top-quark signal events at next-
136 leading-order (NLO) accuracy in the strong coupling
137 constant α_s using the POWHEG [41] generator. The D0 anal-

ysis uses the SINGLETOP [42] event generator, based on NLO COMPHEP calculations that match the event kinematic features predicted by NLO calculations [43, 44]. Spin information in the decays of the top quark and the W boson is preserved for both POWHEG and SINGLETOP.

Kinematic properties of background events associated with the W +jets and Z +jets processes are simulated using the ALPGEN leading-order MC generator [45], and those of diboson processes (WW , WZ and ZZ) are modeled using PYTHIA [46]. The $t\bar{t}$ process is modeled using PYTHIA in the CDF analysis and by ALPGEN in the D0 analysis. Higgs-boson processes are modeled using simulated events generated with PYTHIA for a Higgs-boson mass of $m_H = 125$ GeV. The D0 analysis models the shape and shape uncertainties of the WH production process in the 2-jet, 2- b -tag channel using simulated single-top-quark t -channel events that have been shown to have the same distribution of the discriminant output and to be only a small contamination to the s -channel signal. In all cases PYTHIA is used to model proton remnants and simulate the hadronization of all generated partons. The mass of the top quark in simulated events is set to $m_t = 172.5$ GeV, which is consistent with the current Tevatron average value [1]. All MC events are processed through GEANT-based detector simulations [47] and reconstructed by the same software packages used for the collider data.

Predictions for the normalization of simulated background-process contributions are estimated using both simulation and data. Data are used to normalize the W plus light-flavor and heavy-flavor jet contributions using enriched W +jets data samples that have negligible signal content [30, 35, 48]. All other simulated background samples are normalized to the theoretical cross sections at NLO combined with next-to-next-to-leading-log (NNLL) resummation [24] for t -channel single-top-quark production, at next-to-NLO [49] for $t\bar{t}$, at NLO [50] for Z +jets and diboson production, and including all relevant higher-order QCD and electroweak corrections for Higgs-boson production [51]. Differences observed between simulated events and data in lepton and jet reconstruction efficiencies, resolutions, jet-energy scale (JES), and b -tagging efficiencies are adjusted in the simulation to match the data, through correction functions obtained from measurements in independent data samples.

We form multivariate discriminants, optimized for separating the s -channel single-top-quark signal events in each of the analysis samples from the larger background contributions, to extract the cross section measurements [52]. The combined cross section measurement is obtained using a Bayesian statistical analysis of the observed discriminant distributions from each sample which are compared to the modeled distributions for each of the contributing signal and background processes [53].

Uncertainties on differential distributions (dist) and their normalizations (norm) are categorized by source.

A complete list of systematic uncertainties for the ℓ +jets analyses is given in Table I. The CDF \cancel{E}_T +jets analysis has a similar set of systematic uncertainties that are fully correlated with the CDF ℓ +jets analysis except for the uncertainty related to the data-based background. Sources of systematic uncertainty common to measurements of both collaborations are assumed to be 100% correlated, while other uncertainties are assumed to be uncorrelated. The categories of uncertainty correspond generally to those in Ref. [1, 3], and can be summarized as follows:

Detector-specific luminosity uncertainty: The component of the uncertainty on luminosity that comes from the uncertainty on the acceptance and efficiency of the luminosity detector, which is taken as uncorrelated between the CDF [54] and D0 [55] measurements.

Luminosity from cross section: The portion of the uncertainty in luminosity that comes from uncertainties on the inelastic and diffractive cross sections. It is taken as fully correlated between the CDF and D0 measurements.

Signal modeling: The systematic uncertainty associated with uncertainties in the modeling of the single-top-quark signal, including uncertainties from the choice of the description of initial- and final-state QCD radiation, and proton and antiproton parton density functions. It also covers uncertainties in the applied hadronization models and is taken as fully correlated between the CDF and D0 measurements.

Background from simulation: The systematic uncertainty associated with uncertainties in the modeling of various background contributions are taken as fully correlated between the CDF and D0 measurements. This includes uncertainties in $t\bar{t}$ and diboson process normalizations originating from theoretical calculations.

Background based on data: The systematic uncertainty associated with the modeling of various background sources obtained using data-driven methods which is uncorrelated between the CDF and D0 measurements. This includes uncertainties on the normalization of W +jets, $Wb\bar{b}$, and $Wc\bar{c}$ events as well as uncertainties on the modeling of the contributions and discriminant-variable shapes for the W +jets and QCD multijet production processes.

Detector modeling: The systematic uncertainty on efficiencies for identifying reconstructed objects and to cover observed mismodeling of the data from the simulations. This is uncorrelated between the CDF and D0 measurements.

247 **b -jet tagging:** The systematic uncertainty associated 268
 248 with the modeling of b -jet tagging efficiencies and 269
 249 associated mistag rates. It is uncorrelated between 270
 250 the CDF [39] and D0 [40] measurements. 271

251 **Jet energy scale (JES):** The systematic uncertainty 273
 252 that originates from using calibration-data sam- 274
 253 ples to establish the JES. For the CDF analyses, 275
 254 this corresponds to uncertainties associated with 276
 255 the η -dependent JES corrections, which are esti- 277
 256 mated using dijet events in data. For the D0 anal-
 257 ysis, this includes uncertainties in calorimeter re-
 258 sponse for light jets, uncertainties from η - and p_T -
 259 dependent JES corrections, and other small contri-
 260 butions. This uncertainty is assumed to be uncor-
 261 related between the CDF [56] and D0 [57] measure-
 262 ments.

TABLE I: Systematic uncertainties associated with the CDF and D0 single-top-quark s -channel cross section measurements. The values shown for each category indicate the range of uncertainties applied to the predicted normalizations for signal and background contributions over the full set of analysis samples from each experiment. The black dots indicate which categories contribute uncertainties on the shape of the final multivariate discriminant output variable. It is also noted if categories are treated as fully correlated between the two experiments.

Systematic uncertainty	CDF		D0		Corre- lated
	Norm	Dist	Norm	Dist	
Lumi from detector	4.5%		4.5%		No
Lumi from cross section	4.0%		4.0%		Yes
Signal modeling	2–10%	•	3–8%		Yes
Background (simulation)	2–12%	•	2–11%	•	Yes
Background (data)	15–40%	•	19–50%	•	No
Detector modeling	2–10%	•	1–5%	•	No
b -jet-tagging	10–30%		15–40%	•	No
JES	0–20%	•	9–40%	•	No

The Bayesian posterior probability density as a function of s -channel signal cross section (σ_s) is given by

$$p(\sigma_s) = \int L(\sigma_s, \{\theta\} | \text{data}) \pi(\sigma_s) \Pi(\{\theta\}) d\{\theta\}, \quad (1)$$

where L is the joint binned likelihood function for all channels

$$L = \prod_{i=\text{bins, channels}} \frac{(s_i + b_i)^{n_i} e^{-(s_i + b_i)}}{n_i!}. \quad (2)$$

263 $\{\theta\}$ is the set of nuisance parameters representing the 294
 264 systematic uncertainties, and $\Pi(\{\theta\})$ is the product of 295
 265 the prior probability densities encoding the systematic 296
 266 uncertainties on $\{\theta\}$. The predictions for the number of 297
 267 signal events (s_i) and background events (b_i) depend on 298

the values of the nuisance parameters that are integrated out in Eq. (1). The number of observed events in bin i is n_i . The prior density for the signal cross section, $\pi(\sigma_s)$, is taken to be a uniform prior for non-negative cross sections. We quote the measured cross section as the value that maximizes its posterior likelihood, and the uncertainty as the smallest interval that contains 68% of the integrated area of the posterior density.

Figure 2 shows the signal and background expectation and the data as a function of $\log_{10}(s/b)$ of the collected bins, for the combined CDF and D0 analyses. The ex-

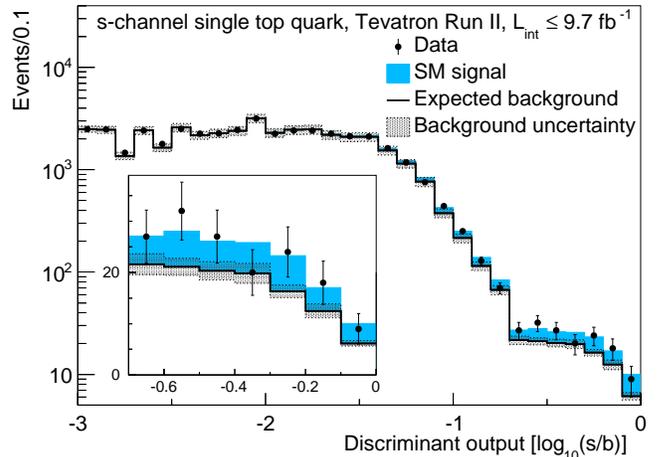


FIG. 2: (Color online) Distribution of the discriminant histograms, summed for bins with similar signal-to-background ratio (s/b). The expected sum of the backgrounds is shown by the unfilled histogram, and the uncertainty of the background is represented by the grey shaded band. The expected s -channel signal contribution is shown by a filled blue histogram.

tracted posterior probability distribution for σ_s is presented in Fig. 3, and Fig. 4 gives a graphical presentation of the individual and combined measurements. All measurements agree within their uncertainties with the SM prediction, $\sigma_s^{SM} = 1.05 \pm 0.06$ pb ($m_t = 172.5$ GeV) [25]. The most probable value for the combined cross section is $\sigma_s = 1.29^{+0.26}_{-0.24}$ pb for a top-quark mass of 172.5 GeV. The total expected uncertainty is 20%, and the expected uncertainty without considering systematic uncertainties is 14%. The dependence of the measured value on the assumed value of the top-quark mass is estimated to be negligible compared to the uncertainty on the measurement [30, 48].

The statistical significance of this result is quantified through a calculated p -value based on an asymptotic log-likelihood ratio approach (LLR) [58]. The p -value quantifies the probability that the measured value of the cross section or a larger value could result from a background fluctuation in the absence of signal. The distributions of LLR resulting from fits of simulated samples that in-

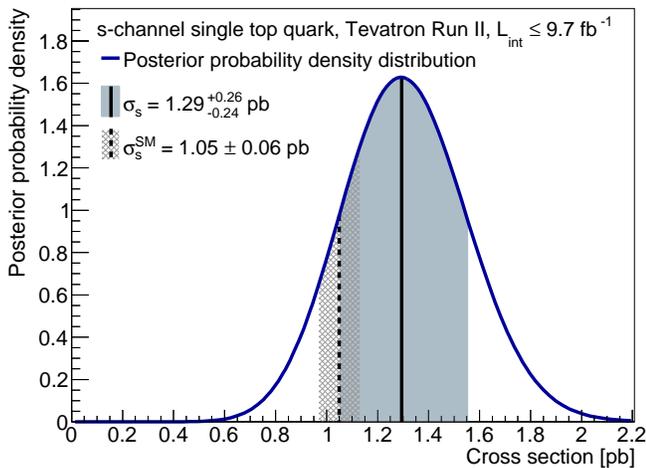


FIG. 3: The posterior probability distribution for the combination of the CDF and D0 analysis channels.

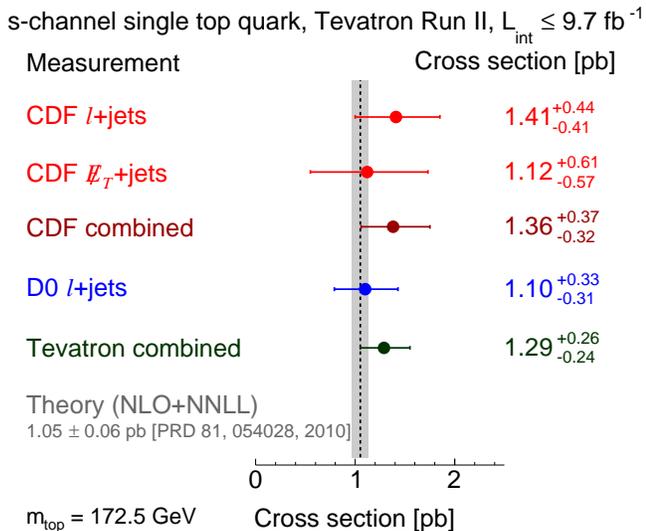


FIG. 4: (Color online) Measured single-top-quark s -channel production cross sections from each of the individual analyses and various combinations of these analyses compared with the NLO+NNLL theoretical prediction [25].

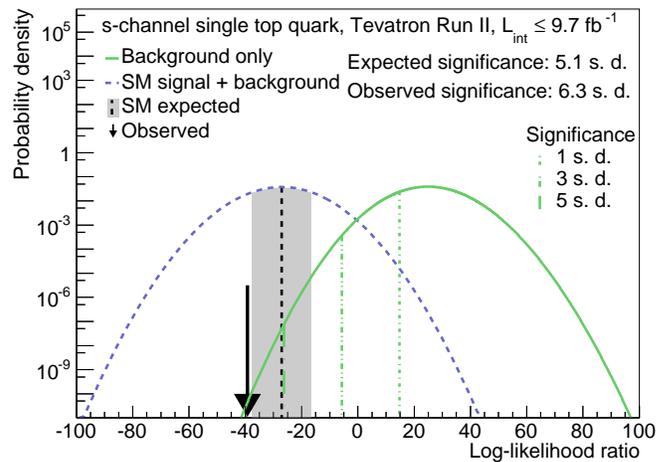


FIG. 5: (Color online) Log-likelihood ratios for the background-only (solid green line) and SM-signal-plus-background (dashed blue) hypotheses from the combined measurement.

311 for a top quark mass of $m_t = 172.5$ GeV, in agreement with the SM expectation.
312

Acknowledgments

313
314 We thank the Fermilab staff and technical staffs of the participating institutions for their vital contributions. We acknowledge support from the DOE and NSF (USA), ARC (Australia), CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil), NSERC (Canada), NSC, CAS and CNSF (China), Colciencias (Colombia), MSMT and GACR (Czech Republic), the Academy of Finland, CEA and CNRS/IN2P3 (France), BMBF and DFG (Germany), DAE and DST (India), SFI (Ireland), INFN (Italy), MEXT (Japan), the Korean World Class University Program and NRF (Korea), CONACyT (Mexico), FOM (Netherlands), MON, NRC KI and RFBR (Russia), the Slovak R&D Agency, the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010 (Spain), The Swedish Research Council (Sweden), SNSF (Switzerland), STFC and the Royal Society (United Kingdom), the A.P. Sloan Foundation (USA), and the EU community Marie Curie Fellowship contract 302103.
315
316
317
318
319
320
321
322

* Deceased

† With visitors from ^aUniversity of British Columbia, Vancouver, BC V6T 1Z1, Canada, ^bIstituto Nazionale di Fisica Nucleare, Sezione di Cagliari, 09042 Monserrato (Cagliari), Italy, ^cUniversity of California Irvine, Irvine, CA 92697, USA, ^dInstitute of Physics, Academy of Sciences of the Czech Republic, 182 21, Czech Republic,

299 clude background-only, or signal-plus-background, contributions are presented in Fig. 5. The probability to
300 measure an s -channel cross section of at least the observed value in the absence of signal is 1.8×10^{-10} ,
301 corresponding to a significance of 6.3 standard deviations (s. d.), with a sensitivity expected from the SM of 5.1
302 s. d.
303
304
305

306 In summary, we report the first observation (≥ 5 s. d.)
307 of s -channel single-top-quark production with a significance of 6.3 s. d. by combining the CDF and D0 mea-
308 surements. The combined value of the s -channel single-
309 top-quark production cross section is $\sigma_s = 1.29^{+0.26}_{-0.24}$ pb
310

- ^eCERN, CH-1211 Geneva, Switzerland, ^fCornell Uni-
 339 versity, Ithaca, NY 14853, USA, ^gUniversity of Cyprus,
 340 Nicosia CY-1678, Cyprus, ^hOffice of Science, U.S. De-
 341 partment of Energy, Washington, DC 20585, USA,
 342 ⁱUniversity College Dublin, Dublin 4, Ireland, ^jETH,
 343 8092 Zürich, Switzerland, ^kUniversity of Fukui, Fukui
 344 City, Fukui Prefecture, Japan 910-0017, ^lUniversidad
 345 Iberoamericana, Lomas de Santa Fe, México, C.P. 01219,
 346 Distrito Federal, ^mUniversity of Iowa, Iowa City, IA
 347 52242, USA, ⁿKinki University, Higashi-Osaka City,
 348 Japan 577-8502, ^oKansas State University, Manhattan,
 349 KS 66506, USA, ^pBrookhaven National Laboratory, Up-
 350 ton, NY 11973, USA, ^qQueen Mary, University of Lon-
 351 don, London, E1 4NS, United Kingdom, ^rUniversity
 352 of Melbourne, Victoria 3010, Australia, ^sMuons, Inc.,
 353 Batavia, IL 60510, USA, ^tNagasaki Institute of Ap-
 354 plied Science, Nagasaki 851-0193, Japan, ^uNational
 355 Research Nuclear University, Moscow 115409, Russia,
 356 ^vNorthwestern University, Evanston, IL 60208, USA,
 357 ^wUniversity of Notre Dame, Notre Dame, IN 46556,
 358 USA, ^xUniversidad de Oviedo, E-33007 Oviedo, Spain,
 359 ^yCNRS-IN2P3, Paris, F-75205 France, ^zUniversidad
 360 Tecnica Federico Santa Maria, 110v Valparaiso, Chile,
 361 ^{aa}The University of Jordan, Amman 11942, Jordan,
 362 ^{bb}Universite catholique de Louvain, 1348 Louvain-La-
 363 Neuve, Belgium, ^{cc}University of Zürich, 8006 Zürich,
 364 Switzerland, ^{dd}Massachusetts General Hospital, Boston,
 365 MA 02114 USA, ^{ee}Harvard Medical School, Boston, MA
 366 02114 USA, ^{ff}Hampton University, Hampton, VA 23668,
 367 USA, ^{gg}Los Alamos National Laboratory, Los Alamos,
 368 NM 87544, USA, ^{hh}Università degli Studi di Napoli Fed-
 369 erico I, I-80138 Napoli, Italy
 370
 371 † With visitors from ⁱⁱAugustana College, Sioux Falls,
 372 SD, USA, ^{jj}The University of Liverpool, Liverpool, UK,
 373 ^{kk}DESY, Hamburg, Germany, ^{ll}Universidad Michoacana
 374 de San Nicolas de Hidalgo, Morelia, Mexico, ^{mm}SLAC,
 375 Menlo Park, CA, USA, ⁿⁿUniversity College London,
 376 London, UK, ^{oo}Centro de Investigacion en Computa-
 377 cion - IPN, Mexico City, Mexico, ^{pp}Universidade ES-
 378 tadual Paulista, São Paulo, Brazil, ^{qq}Karlsruher Institut
 379 für Technologie (KIT) - Steinbuch Centre for Comput-
 380 ing (SCC), ^{rr}Office of Science, U.S. Department of En-
 381 ergy, Washington, D.C. 20585, USA, ^{ss}American Associ-
 382 ation for the Advancement of Science, Washington, D.C.
 383 20005, USA, ^{tt}National Academy of Science of Ukraine
 384 (NASU) - Kiev Institute for Nuclear Research (KINR)
 385 [1] T. Aaltonen *et al.* (CDF and D0 Collaborations),
 386 Phys. Rev. D **86**, 092003 (2012); Tevatron Elec-
 387 troweak Working Group (CDF and D0 Collaborations),
 388 arXiv:1305.3929.
 389 [2] C. T. Hill and S. J. Parke, Phys. Rev. D **49**, 4454 (1994).
 390 [3] T. Aaltonen *et al.* (CDF and D0 Collaborations),
 391 arXiv:1309.7570 [Phys. Rev. D, (to be published)].
 392 [4] N. Cabibbo, Phys. Rev. Lett. **10**, 531 (1963);
 393 M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**,
 394 652 (1973).
 395 [5] M. S. Chanowitz, Phys. Rev. D **79**, 113008 (2009).
 396 [6] J. Alwall, R. Frederix, J.-M. Gerard, A. Giammanco,
 397 M. Herquet, S. Kalinin, E. Kou, V. Lemaitre, and F.
 398 Maltoni, Eur. Phys. J. C **49**, 791 (2007).
 399 [7] T. M. P. Tait and C. P. Yuan, Phys. Rev. D **55**, 7300
 400 (1997).
 401 [8] M. E. Luke and M. J. Savage, Phys. Lett. B **307**, 387
 402 (1993).
 403 [9] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett.
 404 **102**, 151801 (2009).
 405 [10] V. M. Abazov *et al.* (D0 Collaboration), Phys. Lett. B
 406 **693**, 81 (2010).
 407 [11] A. Heinson, A. S. Belyaev, and E. E. Boos, Phys. Rev.
 408 D **56**, 3114 (1997).
 409 [12] V. M. Abazov *et al.* (D0 Collaboration), Phys. Lett. B
 410 **708**, 21 (2012).
 411 [13] V. M. Abazov *et al.* (D0 Collaboration), Phys. Lett. B
 412 **713**, 165 (2012).
 413 [14] E. H. Simmons, Phys. Rev. D **55**, 5494 (1997).
 414 [15] A. Datta, P. J. O'Donnell, Z. H. Lin, X. Zhang, and
 415 T. Huang, Phys. Lett. B **483**, 203 (2000).
 416 [16] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett.
 417 **103**, 041801 (2009).
 418 [17] V. M. Abazov *et al.* (D0 Collaboration), Phys. Lett. B
 419 **699**, 145 (2011).
 420 [18] C. S. Li, R. J. Oakes, and J. M. Yang, Phys. Rev. D **55**,
 421 1672 (1997).
 422 [19] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett.
 423 **102**, 191802 (2009).
 424 [20] T. M. P. Tait and C. P. Yuan, Phys. Rev. D **63**, 014018
 425 (2001).
 426 [21] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett.
 427 **108**, 201802 (2012).
 428 [22] S. S. D. Willenbrock and D. A. Dicus, Phys. Rev. D **34**,
 429 155 (1986).
 430 [23] C.-P. Yuan, Phys. Rev. D **41**, 42 (1990).
 431 [24] N. Kidonakis, Phys. Rev. D **83**, 091503 (2011). The cross
 432 section for the t -channel single-top-quark process is $2.10 \pm$
 433 0.13 pb ($m_t = 172.5$ GeV).
 434 [25] N. Kidonakis, Phys. Rev. D **81**, 054028 (2010). The s -
 435 channel single-top-quark cross section is 1.05 ± 0.06 pb
 436 ($m_t = 172.5$ GeV).
 437 [26] S. Cortese and R. Petronzio, Phys. Lett. B **253**, 494
 438 (1991).
 439 [27] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett.
 440 **103**, 092002 (2009).
 441 [28] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett.
 442 **103**, 092001 (2009).
 443 [29] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. D
 444 **84**, 112001 (2011).
 445 [30] V. M. Abazov *et al.* (D0 Collaboration), Phys. Lett. B
 446 **726**, 656 (2013).
 447 [31] V. M. Abazov *et al.* (D0 Collaboration), Phys. Lett. B
 448 **705**, 313 (2011).
 449 [32] G. Aad *et al.* (ATLAS Collaboration), Phys. Lett. B **717**,
 450 330 (2012).
 451 [33] S. Chatrchyan *et al.* (CMS Collaboration), J. High En-
 452 ergy Phys. **12** (2012) 035.
 453 [34] T. Aaltonen *et al.* (CDF Collaboration),
 454 arXiv:1402.0484.
 455 [35] T. Aaltonen *et al.* (CDF Collaboration),
 456 arXiv:1402.3756.
 457 [36] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **71**,
 458 032001 (2005) [hep-ex/0412071].
 459 [37] V. M. Abazov *et al.* (D0 Collaboration), Nucl. Instrum.
 460 Meth. A **565**, 463 (2006) [physics/0507191 [physics.ins-
 461 det]].
 462 [38] The CDF and D0 experiments use a cylindrical coordi-
 463 nate system with origins in the centers of the detectors,
 464 where θ and ϕ are the polar and azimuthal angles, re-
 465 spectively, and pseudorapidity is $\eta = -\ln[\tan(\theta/2)]$. The
 466 transverse energy, as measured by the calorimeter, is de-

- 467 fined to be $E_T = E \sin \theta$. The missing E_T (\vec{E}_T) is de-493
 468 fined by $\vec{E}_T = -\sum_i E_T^i \hat{n}_i$, i = calorimeter tower number, 494
 469 where \hat{n}_i is a unit vector perpendicular to the beam axis 495
 470 and pointing at the i th calorimeter tower. \vec{E}_T is cor-496
 471 rected for high-energy muons and for mismeasurements 497
 472 of jet energies. We define $E_T = |\vec{E}_T|$. The transverse mo-498
 473 mentum p_T is defined to be $p \sin \theta$. 499
- [39] J. Freeman, T. Junk, M. Kirby, Y. Oksuzian, T. Phillips, 500
 474 F. Snider, M. Trovato, J. Vizan, and W. Yao, Nucl. In-501
 475 strum. Methods A **697**, 64 (2013). 502
- [40] V. M. Abazov *et al.* (D0 Collaboration), Nucl. Instrum. 503
 476 Methods A **620**, 490 (2010); V. M. Abazov *et al.* (D0 504
 477 Collaboration), arXiv:1312.7623. 505
- [41] S. Alioli, P. Nason, C. Oleari, and E. Re, J. High Energy 506
 478 Phys. **09** (2009) 111. 507
- [42] E. E. Boos, V. E. Bunichev, L. V. Dudko, V. I. Savrin, 508
 483 and V. V. Sherstnev, Phys. Atom. Nucl. **69**, 1317 (2006). 509
 484 We use SINGLETOP version 4.2p1. 510
- [43] Z. Sullivan, Phys. Rev. D **70**, 114012 (2004). 511
- [44] J. M. Campbell, R. Frederix, F. Maltoni, and F. Tram- 512
 486 tano, Phys. Rev. Lett. **102**, 182003 (2009). 513
- [45] M. L. Mangano, M. Moretti, F. Piccinini, R. Pittau, and 514
 488 A.D. Polosa, J. High Energy Phys. **07** (2003) 001. We use 515
 489 ALPGEN version 2.11. 516
- [46] T. Sjöstrand, S. Mrenna, and P. Skands, J. High Energy 517
 491 Phys. **05** (2006) 026. We use PYTHIA version 6.409.
- [47] R. Brun and F. Carminati, CERN Program Library Long
 Writeup, Report No. W5013, 1993.
- [48] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. D
82, 112005 (2010).
- [49] S. Moch and P. Uwer, Phys. Rev. D **78**, 034003 (2008).
 The top-quark-pair cross section is 7.46 ± 0.75 pb ($m_t =$
 172.5 GeV).
- [50] R. K. Ellis, Nucl. Phys. Proc. Suppl. **160**, 170 (2006).
 We use MCFM version 5.1.
- [51] J. Baglio and A. Djouadi, J. High Energy Phys. **10** (2010)
 064.
- [52] For the D0 collaboration this is different from Ref. [30],
 where a combined s and t -channel discriminant was used
 to measure separately both single top quark channels,
 without assuming their SM cross sections when each is
 considered a background to the other process.
- [53] I. Bertram *et al.*, FERMILAB-TM-2104 (2000).
- [54] S. Klimenko, J. Konigsberg, and T. M. Liss,
 FERMILAB-FN-0741.
- [55] T. Andeen *et al.*, FERMILAB-TM-2365 (2007).
- [56] A. Bhatti *et al.*, Nucl. Instrum. Methods A **566**, 2 (2006).
- [57] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. D
85, 052006 (2012).
- [58] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, Eur.
 Phys. J. C **71**, 1554 (2011).